

# Range Ambiguity Smearing and Suppression: Comparison of Different Azimuth Phase Codes and Opportunities from Multi-Focus Post-Processing

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## Abstract

Synthetic aperture radar (SAR) remote sensing has become very attractive in Earth observation applications, since it provides high resolution imaging independent of weather conditions and sunlight illumination. However, the design of a SAR system is still constrained by nadir returns and range ambiguities, which can strongly corrupt the quality of the SAR image, if not avoided. Recently, a novel SAR concept, named waveform-encoded SAR, based on pulse-to-pulse variation of the transmitted waveform and on a dual/multi-focus post-processing, has been proposed in order to cope with these ambiguities. While some implementation issues related to waveform variation are still under analysis, this work investigates the potentialities of a thresholding and blanking approach for suppressing range ambiguities and a simpler variant, where waveform encoding is replaced by azimuth phase coding and multi-focus post-processing is always performed. In particular, real TerraSAR-X data are exploited to simulate and assess the range ambiguity smearing capability of a “Doppler-matched” azimuth phase code as well as of a waveform-encoded SAR. First results show that range ambiguity suppression through this approach is only effective for very strong ambiguities.

## 1 Introduction

Synthetic aperture radar (SAR) is a very attractive remote sensing technique for the systematic observation of dynamic processes on the Earth's surface since it provides high resolution images independent of weather conditions and sunlight illumination [1]-[5].

As a consequence of the SAR pulsed operation and side-looking geometry, the so-called range ambiguities, i.e., echoes coming from different places on the ground and also corresponding to different transmitted pulses compared to the imaged target, can be superimposed on the useful signal, thus strongly corrupting the quality of the SAR image [2], [6]. In order to avoid these ambiguities, a narrow antenna beam is usually considered; however, this corresponds to an increased antenna elevation dimension, thus constraining the design of a SAR system [7].

A novel SAR concept, namely waveform-encoded SAR [8]-[11], based on pulse-to-pulse variation of the transmitted waveform, has been proposed to remove the nadir echo within a post-processing step and relax the system design constraints. In this paper the further advantages of this concept to smear and suppress range ambiguities are investigated. Such a system, in fact, might allow focusing range ambiguities in order to suppress them, while smearing the useful signal in an intermediate processing step. A thresholding and blanking approach has been proved to be an effective means for ambiguity suppression while keeping the useful signal as unaffected as possible. The overall performance depends on the distribution and level of the ambiguities (the weaker the ambiguity the harder its suppression) and thus makes a further investigation of the intensity distribution in real images necessary.

A further possibility for suppressing range ambiguities is to replace waveform encoding with azimuth phase coding [13]-[15]; this allows actually changing the ambiguity in the range-Doppler domain, after having applied an azimuth phase modulation to the transmitted pulses and a corresponding demodulation to the received ones. Also, an azimuth filter can be applied in the range-Doppler domain depending on the azimuth phase code used in order to suppress the ambiguity. As described in the literature, azimuth phase coding (APC) is simply characterized by three steps [13]:

- azimuth phase modulation to the transmitted pulses;
- corresponding demodulation to the received pulses;
- azimuth filtering.

The first step impacts the SAR system since every transmit pulse is furthermore modulated by a phase factor  $e^{j\varphi(n)}$ , which depends on the pulse number  $n$ . A corresponding demodulation with a phase factor  $e^{-j\varphi(n)}$  completely eliminates the modulation of the backscattered signal coming from the echo of interest (illuminated target). However, it does not completely cancel the modulation of range ambiguities as they come from preceding or successive transmitted pulses. As a consequence, the modulation / demodulation process leaves a residual phase factor  $e^{j\varphi(n+k)-j\varphi(n)}$ , depending on the  $k^{\text{th}}$  order of ambiguity, which changes the ambiguity distribution in the range-Doppler domain as well as in the time domain. Depending on the azimuth phase code used, an azimuth filter enables suppressing part of the ambiguous energy by filtering it using a processed Doppler bandwidth (PBW)

smaller than the considered pulse repetition frequency (PRF).

The suppression of range ambiguities might allow relaxing the constraints on PRF selection in SAR system design, i.e., might allow the PRF to exceed the upper limit imposed by the antenna elevation dimension, at the negligible cost of applying an azimuth phase modulation to the transmitted waveforms.

This work aims to assess the ambiguity smearing capability of a ‘‘Doppler-matched’’ azimuth phase code and, similarly to a waveform-encoded SAR, the joint exploitation of azimuth phase coding (instead of waveform encoding) and multi-focus post-processing. In particular, real TerraSAR-X data are used to ensure our smearing expectations and to assess opportunities from multi-focus post-processing through the investigation of intensity distributions.

The paper is structured as follows. In Section 2 the methodology for simulating the range ambiguity and the useful signal is presented, together with the modulation / demodulation process and the investigated azimuth phase codes. Section 3 shows the results based on point-like target simulations. In Section 4, the results based on simulations using real TerraSAR-X data are presented together with an investigation of opportunities from multi-focus post-processing for range ambiguities suppression, while in Section 5 the conclusions and some outlooks are reported.

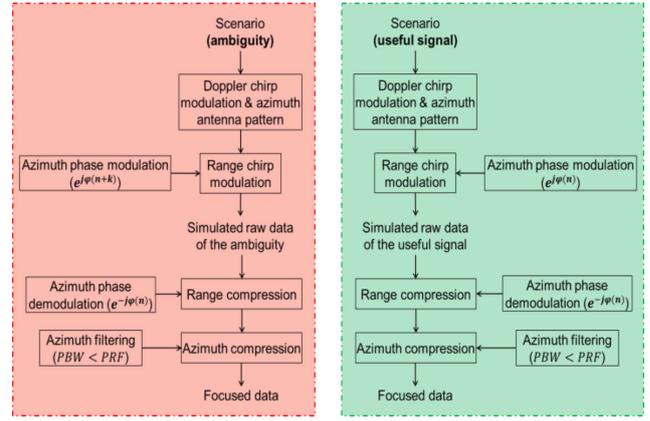
## 2 Proposed methodology

The range ambiguity and the useful signal are simulated starting from two portions of a TerraSAR-X image (assumed to correspond to the backscattered distributions of the imaged scene and the scene that is generating the ambiguity). Raw SAR data are generated using the X-band system parameters in **Table 1**.

**Figure 1** shows the proposed methodology with the required processing in order to obtain the focused data. After range compression the modulation / demodulation process leaves a residual phase in the range ambiguity depending on its order (for simplicity, only the first order range ambiguity is considered). Actually, the ambiguity is scaled using a scaling factor in order to simulate the attenuation of the antenna pattern as well as several levels of ambiguity. Also, the raw data of the total signal are simply obtained by adding the contributions from the

Parameter	Value
Wavelength	0.03 m
Orbit height	628 km
Target’s slant range	700 km
Antenna length	8 m
Chirp duration	34.1 $\mu$ s
Chirp bandwidth	40 MHz
Range sampling frequency	44 MHz
PRF	2800 Hz
Processed Doppler bandwidth	2000 Hz

**Table 1** System and processing parameters.



**Figure 1** Proposed methodology for simulating azimuth phase coding (APC) for range ambiguity suppression.

useful and ambiguous signals.

Three azimuth phase codes are considered, despite only the last two will be further investigated:

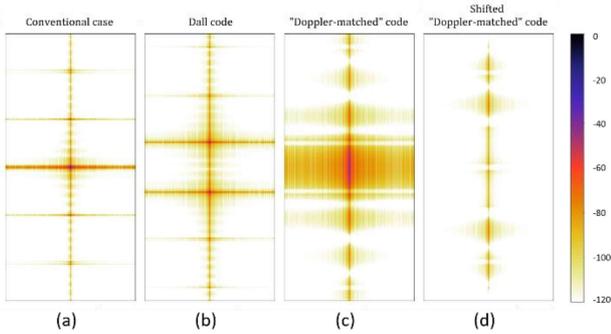
- The Dall code proposed in [14] with the azimuth phases given by  $\phi = [0, 0, \pi, \pi]$  that allows suppressing only odd range ambiguities by shifting their Doppler spectrum by  $PRF/2$ .
- The ‘‘Doppler-matched’’ azimuth phase code proposed in [16], [17] that allows eliminating the quadratic component of the phase of the ambiguous signal, thus leaving just a linear term corresponding to a single frequency for each point scatterer in the scene.
- A shifted ‘‘Doppler-matched’’ azimuth phase code obtained from the ‘‘Doppler-matched’’ azimuth phase code through an additional modulation by  $\phi = [0, \pi]$ .

## 3 Point-like target simulations

Some results concerning point-like target simulations are here presented to point out the smearing capability and in general the properties of the investigated azimuth phase codes. The ambiguity smearing in range and azimuth for different SAR modes is analyzed and described by simple formulas in [18]. In particular, no multi-focus post-processing is here considered.

Unlike a conventional SAR without waveform or phase encoding, where the range ambiguity is completely superimposed on the imaged target (it is slightly defocused because of a mismatched filter) as its Doppler spectrum still follows the behavior of the azimuth antenna pattern, the range ambiguity shifts by  $PRF/2$  in the range-Doppler domain if the Dall code is used, as the residual phase changes by  $\pi$  between successive pulses.

The ‘‘Doppler-matched’’ azimuth phase code in [16], [17] enables eliminating the quadratic component of the phase of the ambiguous signal, thus leaving just a linear term corresponding to a strong single frequency for each point target in the scene (the range ambiguous data appear ‘‘focused’’ in the range-Doppler domain while the desired image signal is defocused).



**Figure 2** Range ambiguity behavior [dB] when focusing using a filter matched to the useful signal. (a) Conventional SAR without waveform or phase encoding. (b) Dall code. (c) “Doppler-matched” code. (d) Shifted “Doppler-matched” code. Slant range (x-axis) corresponds to a 3.5 km interval, while azimuth (y-axis) corresponds to a 20.1 km interval.

A shifted “Doppler-matched” code is obtained from the “Doppler-matched” azimuth phase code by furthermore modulating it to get an additional residual phase of  $\pi$  and to consequently shift the single frequency in the range-Doppler domain by  $\text{PRF}/2$ .

Similarly to a waveform-encoded SAR, an azimuth filter partially eliminates the ambiguity by simply considering a processed Doppler bandwidth smaller than the considered PRF. However, for the “Doppler-matched” and shifted “Doppler-matched” codes the results depend on the azimuth position of the target that generates the ambiguity. Depending on the position, in fact, the ambiguity will be mapped to a specific Doppler frequency, which could fall within or outside the processed Doppler bandwidth and in the former case be more or less attenuated by the Hamming window depending on the Doppler frequency itself.

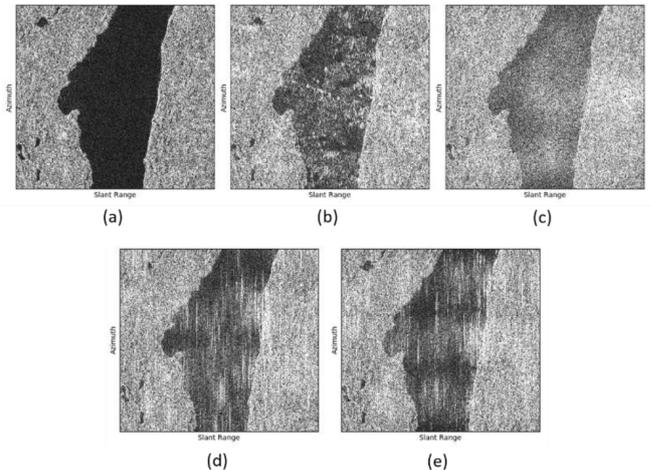
**Figure 2** shows how the range ambiguity behaves when performing a focusing matched to the imaged target. In particular, the properties of the three investigated azimuth phase codes (b)-(d) are displayed for a point-like target scenario and with reference to a conventional SAR without waveform or phase encoding (a). Also, we assume that the ambiguity of the target is mapped to zero-Doppler frequency for the “Doppler-matched” code and we consider a wide azimuth axis in order to see also azimuth ambiguities.

For a conventional SAR (a), the ambiguity appears as slightly defocused because of a mismatched filter, while if using a Dall code (b) the ambiguity shifts by  $\text{PRF}/2$  in the range-Doppler domain as well as in the focused domain. A very interesting property can be observed when using the “Doppler-matched” azimuth phase code (c): the ambiguity is completely smeared along azimuth because of the single frequency in the range-Doppler domain. This suggests implementing a multi-focus post-processing with a thresholding and blanking approach in order to suppress the range ambiguity, as described in Section 4.1. Also, a shifted “Doppler-matched” code (d) allows for a considerable suppression of the range ambiguity (for a point-like

target scenario), as the single frequency moves outside the processed Doppler bandwidth.

## 4 Real TerraSAR-X simulations

As described in Section 3, the “Doppler-matched” phase code allows for a complete smearing of the ambiguity along azimuth in the time domain while making it appearing as “focused” in the range-Doppler domain. This suggests to further investigate the opportunities of both the “Doppler-matched” and shifted “Doppler-matched” phase codes for ambiguity suppression by multi-focus post-processing, using simulations based on real TerraSAR-X data. Two portions of a TerraSAR-X image acquired over the Greater Munich area, Germany, have been used to generate raw data for the ambiguity and the imaged target, as described in Section 2: the scenario simulates the range ambiguity of the Munich city, after having amplitude-scaled it through a scaling factor equal to -10 dB (that corresponds to an extremely strong range ambiguity), on Lake Starnberg. The achieved results in terms of smearing are here compared to the ones of a waveform-encoded SAR with cyclically-shifted chirps on transmit. Unlike a waveform-encoded SAR, which smears the range ambiguities along both range and azimuth in the focused domain by using a sequence of different waveforms on transmit, the “Doppler-matched” (as well as the shifted “Doppler-matched”) code smears the range ambiguities only along azimuth. Also, the ambiguities appear as “focused” in the range-Doppler domain and distributed along the various Doppler frequencies, where the different frequencies correspond to different point scatterers at different azimuth positions.



**Figure 3** Focused data, where useful and ambiguous signals are superimposed (x- and y-axes correspond to slant range and azimuth, respectively) and without considering multi-focus post-processing. (a) Reference, ambiguity-free image. (b) Conventional SAR. (c) Waveform-encoded SAR with cyclically-shifted chirps on transmit. (d) “Doppler-matched” azimuth phase code. (e) Shifted “Doppler-matched” azimuth phase code.

In **Figure 3**, the smearing capability of the “Doppler-matched” code (non-shifted (d) and shifted (e)) is shown with reference to the ambiguity-free image (a) (where only the imaged target is present without ambiguity), a conventional SAR (b) without waveform or phase encoding and a waveform-encoded SAR (c) with cyclically-shifted chirps on transmit.

#### 4.1 Multi-focus post-processing

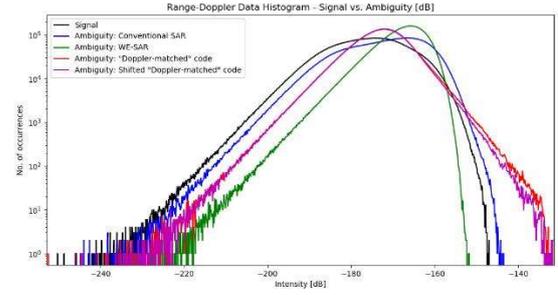
Exploiting the property of the “Doppler-matched” azimuth phase code (complete smearing along azimuth in time domain), it is of interest to understand whether it is possible to further suppress range ambiguities through some post-processing similarly to a waveform-encoded SAR [8]-[11].

In waveform-encoded SAR, a multi-focus post-processing allows highlighting the range ambiguity by means of a matched filter, in order to remove it, while smearing the useful signal using a mismatched filter; an inverse focusing operation then allows returning back to the raw data, which are finally focused again, but using a filter matched to the imaged target, thus obtaining a focused image free of ambiguity.

Similarly, the same procedure can be applied to the case of the “Doppler-matched” phase coding.

As an alternative, the removal of the range ambiguity could be performed in the range-Doppler domain when focusing using a filter matched to the useful signal, if the “Doppler-matched” (both non-shifted and shifted) azimuth phase code is used. The ambiguity, in fact, appears as “focused” while the target energy is spread over Doppler frequencies. This allows speeding up the processing compared to the option above, but the range ambiguity is not perfectly focused, due to a mismatch in the azimuth compression filter (the phase history of the target is used instead of the one of the ambiguity).

The plot in **Figure 4** shows the intensity distribution of the focused data in the range-Doppler domain corresponding to the useful and ambiguous signals and for the two investigated “Doppler-matched” azimuth phase codes as well as for a waveform-encoded SAR and a conventional SAR without waveform or phase encoding. In particular, the black and blue lines, corresponding to the useful signal and to the range ambiguity in case of a conventional SAR system without waveform or phase encoding, respectively, follow the same behaviour since the energy spreading over Doppler frequencies is strictly related to the shape of the azimuth antenna pattern. Instead, a waveform-encoded SAR with cyclically-shifted chirps on transmit smears range ambiguities in both time and range-Doppler domains as a consequence of using different and orthogonal waveforms, thus leading to an almost uniform Doppler spectrum. This energy smearing over Doppler frequencies can be identified by the steeper behaviour of the green line compared to all the other distributions. On the contrary, the red and magenta lines, corresponding to the “Doppler-matched” and shifted “Doppler-matched” azimuth phase codes, respectively, show a smoother behaviour of the intensity distribution of the range



**Figure 4** Intensity distributions of the focused data in the range-Doppler domain corresponding to the useful (black line) and ambiguous (blue, green, red and magenta lines) signals for the different techniques, when focusing using a filter matched to the useful signal. The blue line refers to a conventional SAR without waveform or phase encoding, the green line refers to a waveform-encoded SAR with cyclically-shifted chirps on transmit, while the red and magenta lines correspond to the “Doppler-matched” and shifted “Doppler-matched” azimuth phase codes, respectively.

ambiguity in the range-Doppler domain, as a consequence of more “focused” features due to the removal of the quadratic component of the ambiguous phase.

The smearing capabilities of the “Doppler-matched” azimuth phase code in time domain and the corresponding “focused” features in range-Doppler domain are very interesting and suggest a deeper investigation of more advanced post-processing techniques in order to remove range ambiguities. Also, one could think about a joint exploitation of waveform and phase encoding in order to improve the ambiguity smearing; on transmit, for example, one could consider a combination of up- and down-chirps, which smear range ambiguities mainly along range, and a “Doppler-matched” azimuth phase code which, at the same time, completely smears them also along azimuth [18].

## 5 Conclusion

This work compares different azimuth phase codes and investigates a concept based on azimuth phase encoding and multi-focus post-processing. Simulations based on real TerraSAR-X data have been conducted to prove the effectiveness of the proposed technique in terms of ambiguity smearing (only along azimuth), also suggesting implementing some post-processing, similarly to a waveform-encoded SAR (but in the range-Doppler domain), in order to further suppress range ambiguities. Moreover, a joint exploitation of waveform and phase encoding could be further investigated in order to achieve higher ambiguity smearing, as well as more advanced post-processing techniques for better removing range ambiguities while keeping a negligible corruption of the useful signal.

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